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Real-Time Fiber Optic Strain and Shape Sensing (FOSS) Technology

In-Space Non-Destructive Inspection Technology Workshop

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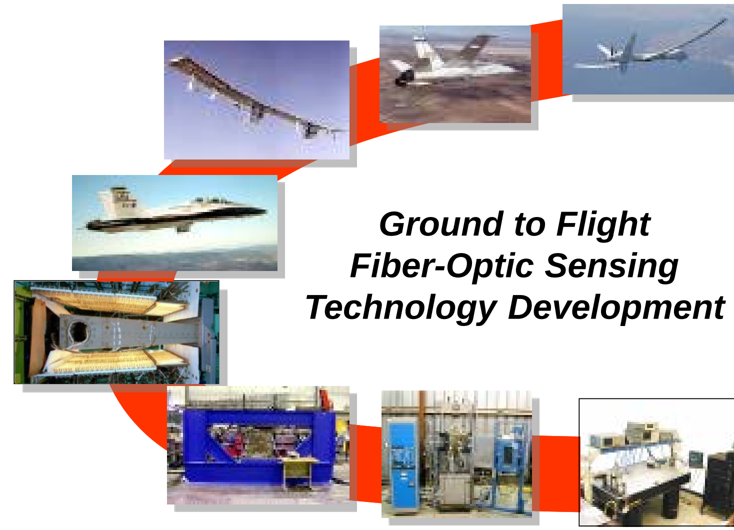
Background: FOSS History

- **NASA Dryden's Aerostructures Branch initiated fiber-optic instrumentation development effort in the mid-90's**
  - Dryden effort focused on atmospheric flight applications of Langley patented OFDR demodulation technique
- **Dryden collaborated on X-33 IVHM Risk Reduction Experiment on F/A-18 System Research Aircraft**
  - Focused on validating vendor's FO VHM system
    - Flew fiber optic instrumented flight test fixture with limited success due to problem with laser
  - Contractor's system limited to 1 sample every 30 seconds
- **Dryden initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight**



X-33 IVHM Risk Reduction Experiment

Background: Advantages over Conventional Sensors

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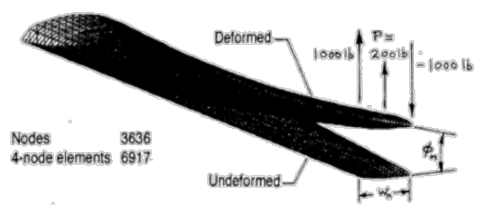
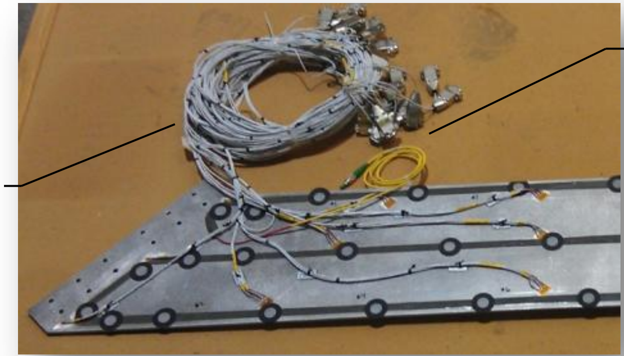
- **Unrivaled density of sensors for spatially distributed measurements**
- **Measurements immune to EMI, RFI and radiation**
- **Lightweight sensors**
  - Typical installation is 0.1 - 1% the weight of conventional gage installations (based on past trade studies)
  - 1000's of sensors on a single fiber (up to 80 feet per fiber)
  - No copper wires
- **With uniquely developed algorithms, these sensors can determine out-of-plane displacement and load at points along the fiber**
- **Small fiber diameter**
  - Approximately the diameter of a human hair
  - Unobtrusive installation
  - Fibers can be bonded externally or applied as a 'Smart Layer' top ply
- **Single calibration value for an entire lot of fiber**
- **Wide temperature range (cryogenic – 550F)**

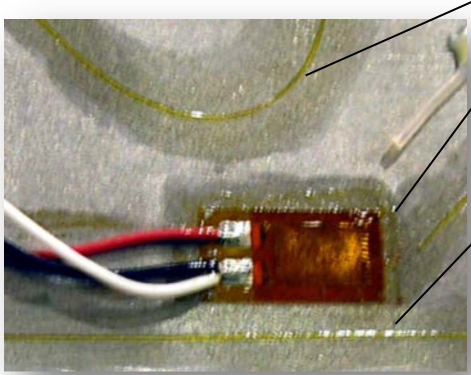
$$y_n = \frac{\Delta l^2}{6c}\left\{(3n-1)\varepsilon_0 + 6\sum_{i=1}^{n-1}(n-i)\varepsilon_i + \varepsilon_n\right\}$$



Wires for *21* strain gage measurements



Fiber for *628* FOSS sensors



Fiber optic sensor

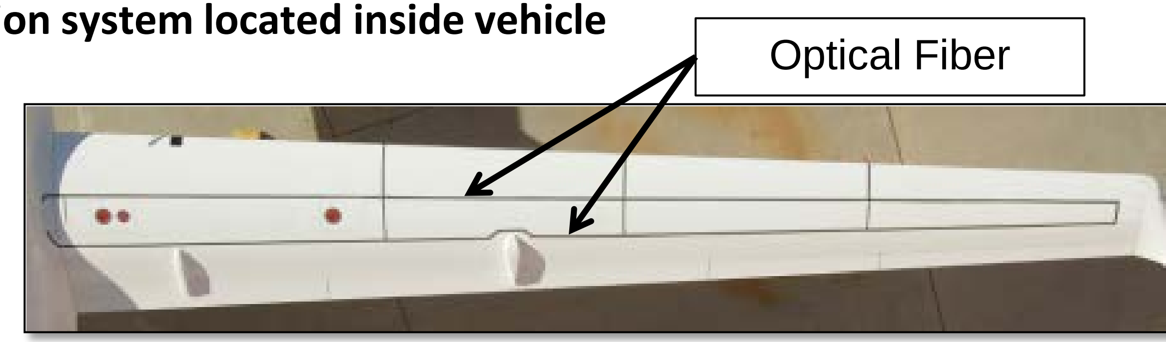
Strain gage

Fiber optic sensor

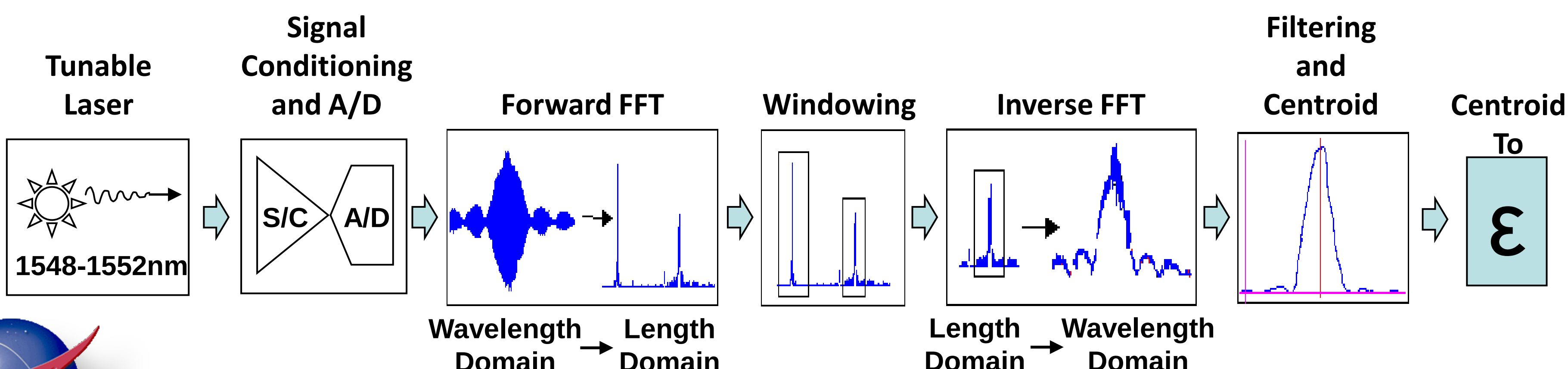
Background: Strain Sensing Process

Sensor Installation

- **Fiber typically installed on surface, but can also be embedded**
  - Minimal impact to outer surface
  - Fiber layout tailored to suit application
- **Interrogation system located inside vehicle**



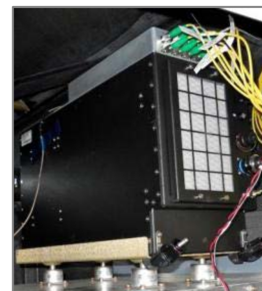
Sensor Interrogation



Recent Development: System Enhancement

- **Increased fiber count**
  - 4-fiber capacity (2008)
  - 8+ fiber capacity (2011)
- **Polarization mitigation**
- **Increased sampling rate**
  - 30 samples per second (2008)
  - 60+ samples per second (2011)

Flight Systems



Ground Systems

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Recent Development: 8-Fiber Flight System

- **Flight system specifications**

Fiber count	8
Max fiber length	80 ft
Max sensing length	40 ft
Max sensors / fiber	960
Total sensors / system	7680
Sample rate	8 fibers @ 60 sps
Power	28VDC @ 5 Amps
User Interface	Ethernet
Weight (non-optimized)	29 lbs
Size (non-optimized)	7.5 x 13 x 17 in

- **Environmental qualification specifications for flight system**

Shock	8g
Vibration	1.1 g-peak sinusoidal curve
Altitude	25kft at -56C for 60 min
Temperature	-56 < T < 40C

Flight system installed in aircraft

Global Observer in Flight

Recent Development: Commercialization

- **Technical Highlights**
  - 4DSP has licensed NASA technology to commercially develop FOSS systems
    - http://www.4dsp.com/RTS150.php
  - Single laser greatly reduces cost per sensor
  - High fiber count systems
    - Modular design with 8 channels per card
    - Expandable
    - Up to 32 fibers possible
    - Up to sensing 80 feet per fiber
  - 11” x 7” x 12”
  - 100 Hz max sample rate
  - Lightweight system for multitude of sensors
    - Approximately 25 lbs
- **Cost**
  - 8 fiber system approx $100K
    - Up to 16,000 sensors
  - 32 fiber system approx $150K
    - Up to 64,000 sensors
  - System can be flight-certified (+$30K)
    - Low power requirements (<10 Amps at 28 Volts DC)

- **Applications**
  - Transport Aircraft
  - Ships
  - Civil Structures
  - Ground Testing

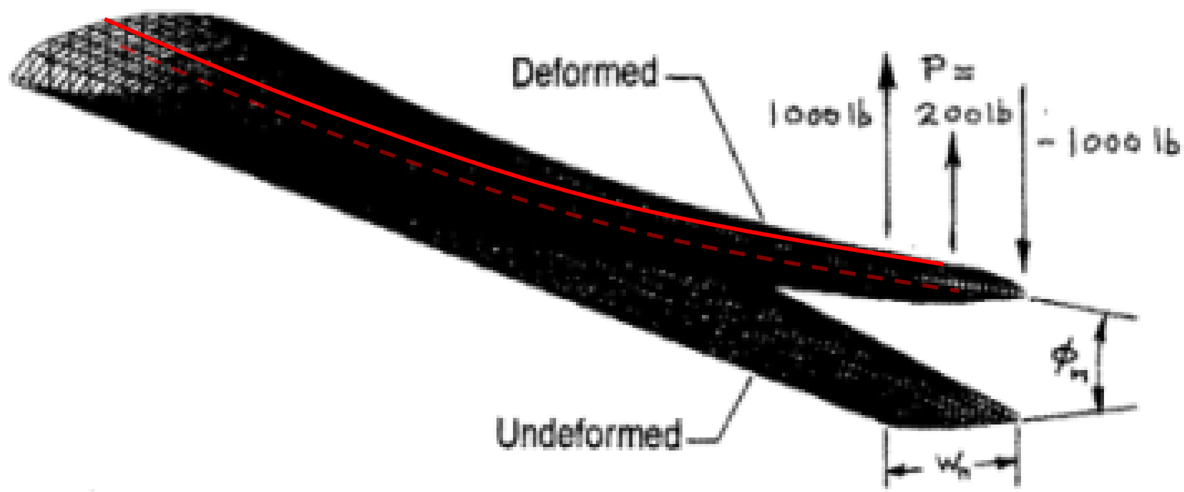
Shape Sensing Algorithms

- **Two types of shape sensing algorithms are developed at NASA**
  - Structural Shape determination through strain
    - Structural shape (such as wing shape deflection) can be determined in real-time via fiber optics sensors
    - Technology has been patented and validated from laboratory to deployment of flight testing
  - Shape determination through intelligent strain fiber
    - Strain information is obtained and calculated into location data due to the fiber unique characteristic
    - Real-time shape data of structure is obtained from the bending of the fiber
    - Technology is currently being validated in the laboratory

Recent Development: Structural Algorithms

- **Structural Shape**
  - Real-time wing shape measurement using fiber optics sensors
    - (Ko, Richards; Patent 7,715,994)

- **Externally applied loads**
  - Real-time applied loads on complex structures using fiber optic sensors
    - (Richards, Ko; Patent 7,520,176)



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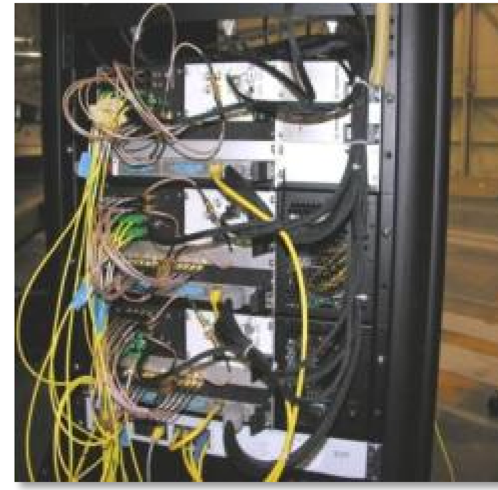
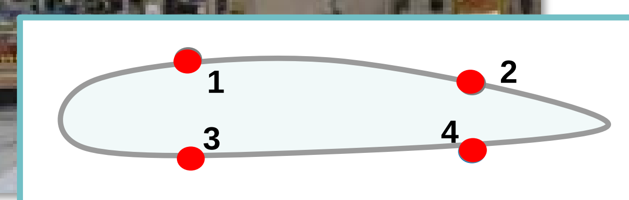
Recent Development: Structural Algorithms

AeroVironment's Global Observer Wing Loads Test

- **Full-scale wing, 175-ft span**
  - Distributed load applied using whiffle trees
- **Two load tests with different design limit loads (DLL)**
  - Positive: +3g's, Negative: -1g
- **18 fibers installed (~17,200 sensors) in 4 lines**
  - Aligned with forward and aft spars, top and bottom





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Recent Development: Structural Algorithms

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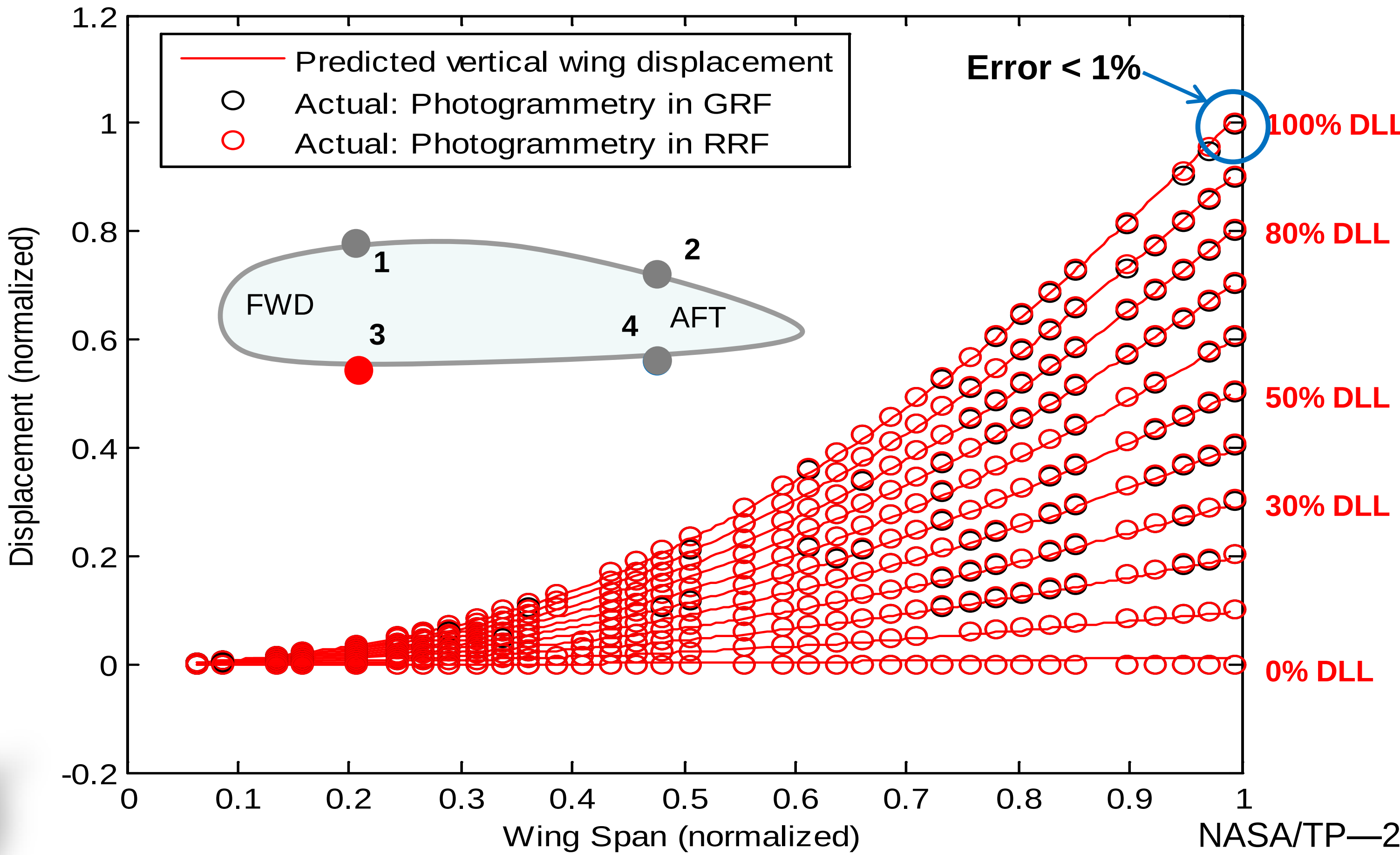
AeroVironment's Global Observer Wing Loads Test

- FOSS strains used to interpret shape using NASA's single fiber shape algorithm
- Photogrammetry provided validation information for wing shape prediction
- **Result: Deflection calculations accurate within inches (13' max deflection)**



NASA/TP—2011-215975

Recent Development: Validation Opportunities

- **Predator-B Flight Testing**
  - 18 flights tests conducted; 36 flight-hours logged
  - Conducted first flight validation testing April 28, 2008
  - Believed to be the first flight validation test of FBG strain and wing shape sensing
  - Multiple flight maneuvers performed
  - Two fiber configurations
  - Fiber optic and conventional strain gages show excellent agreement
  - FBG system performed well throughout entire flight – no issues

Video clip of flight data superimposed on Ikhana photograph

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Recent Development: Validation Opportunities

- **Global Observer Flight Testing**
  - 8-channel system developed and successfully used
  - Validated strain predictions along the left wing using eight, 40ft fibers
  - An aft fuselage surface fiber was installed to monitor fuselage and tail movement
  - Strain distributions were measured along the left wing centerline top and bottom as well as along the trailing edge top and bottom.
  - 8 of the 9 total fibers are attached to the system at any give time

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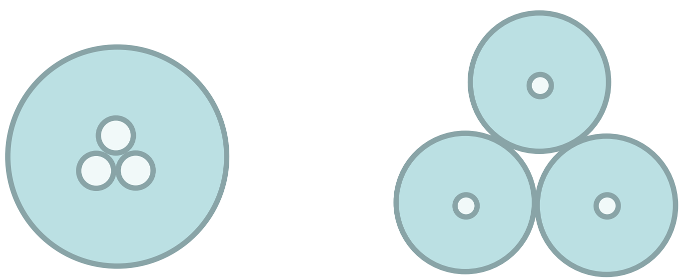
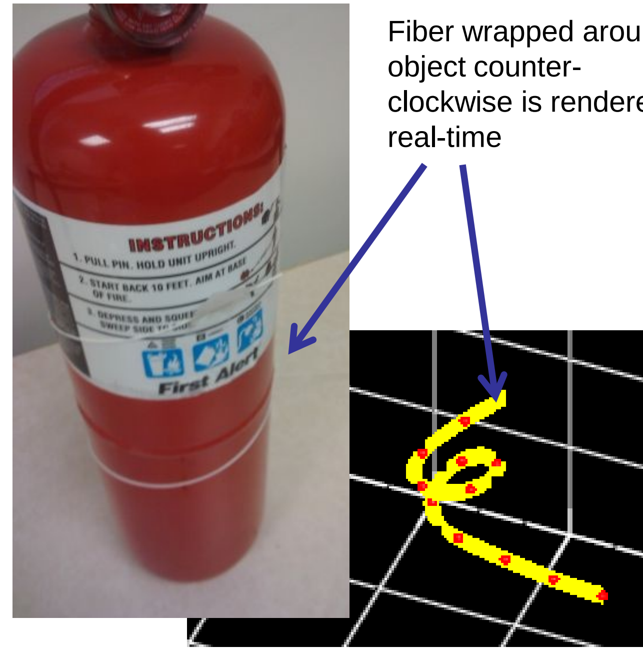
Current Research: 3-Core Shape Measurement

- From collaboration with NASA LaRC, shape sensing using fiber strain sensors has been realized
- Initial research focuses upon 3-core fiber
- This specialty fiber can be replaced with 3 conventional fibers superposition from one another at 120 degrees
- From knowing the strain value of each fiber, the 3-dimensional position of the fiber can be correctly rendered in real-time

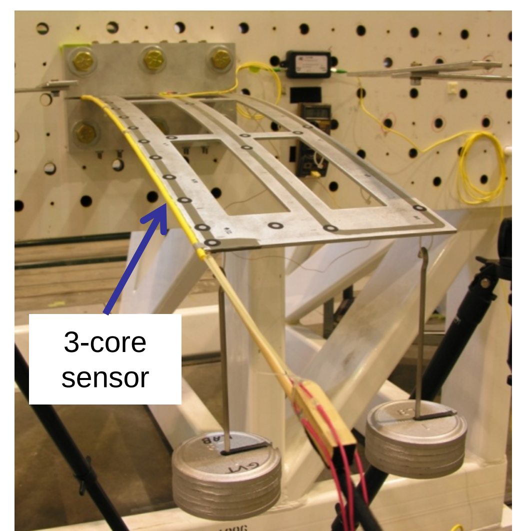


3 core fiber

3 SMFs aligned in 120°

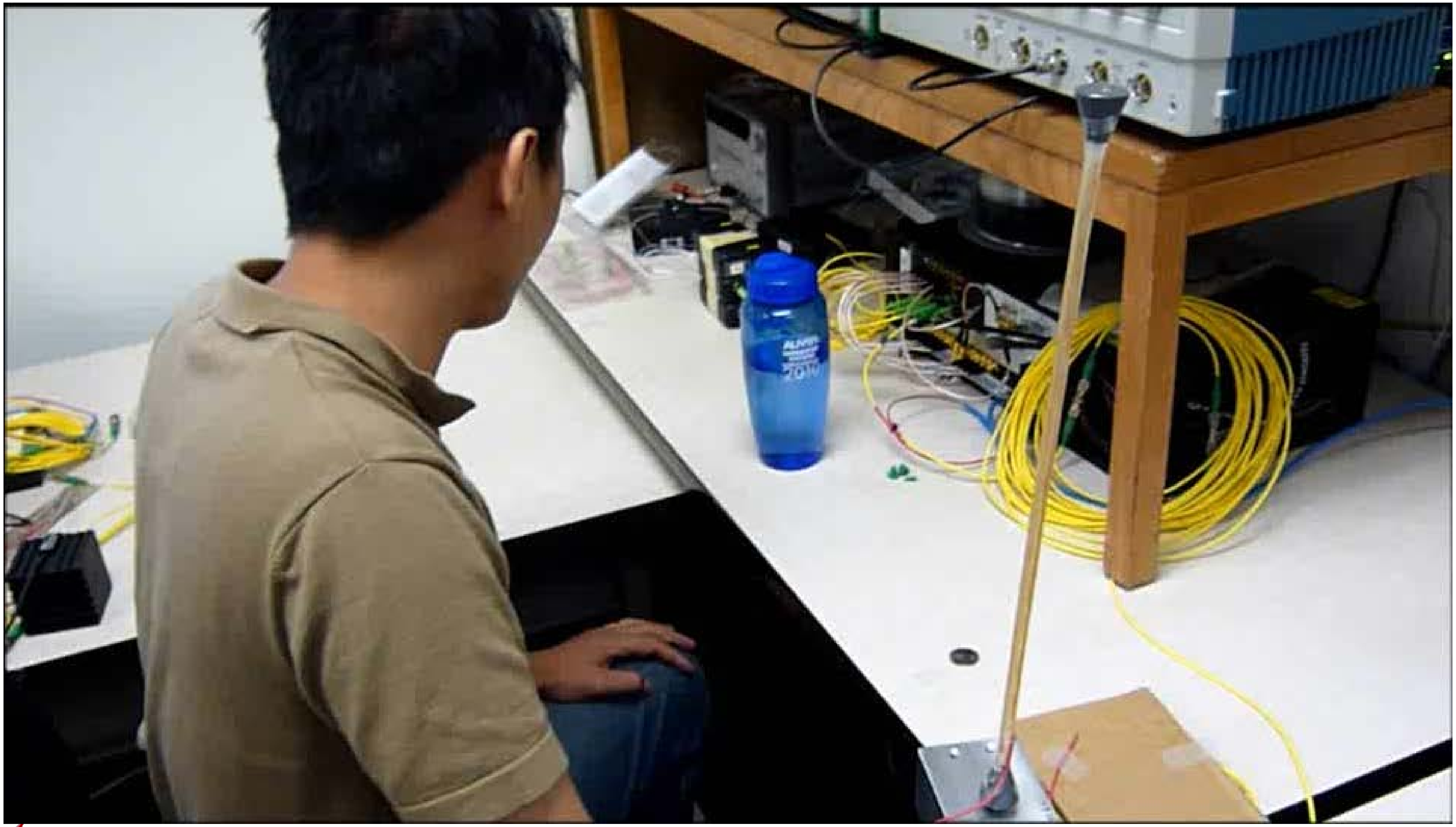


Fiber wrapped around object counter-clockwise is rendered in real-time



Current Research: 3-Core Shape Measurement

- **Real-time shape sensing video demonstration**



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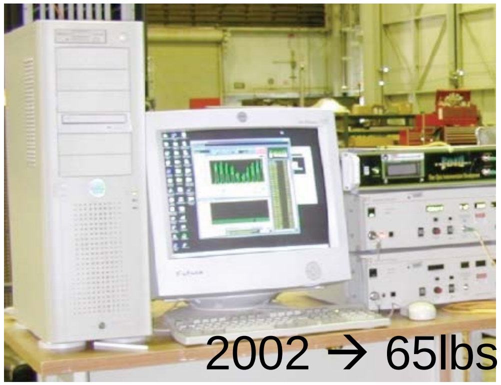
Summary

- **NASA DFRC has successfully develop fiber optics strain sensors technology from laboratory to real-world application**



- **Current status**
  - Dryden FBG system are installed on Ikhana and Global Observer UAV for real time strain sensing
  - Real-time fiber shape sensing is currently being developed
- **Potential application of technology beyond aeronautics**
  - Automotive Sector
  - Energy Sector
  - Biomedical Sector